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In-Axis and Cross-Axis Characterization of the ENDEVCO 7270A Accelerometer in a TO5 Mechanical Package

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Abstract

The characteristics of the ENDEVCO 7270A-60K* piezoresistive accelerometer in a TO5 mechanical package are documented in this report. Both time-domain and frequency domain results are presented. This study was conducted because the TO5 mechanical package is a candidate for high volume production of the ENDEVCO 7270A* and was performed at Sandia National Laboratories in the Mechanical Shock Laboratory. A titanium Hopkinson bar with an ENDEVCO 7270A* in a TO5 mechanical package on a flyaway fixture in two different orientations was used for in-axis characterization up to 25,000 g. for a bandwidth of DC - 10,000 Hz. The reference measurement for the in-axis characterization is a certified, commercial, laser doppler vibrometer*. The cross-axis performance of the ENDEVCO 7270A* in a TO5 mechanical package was determined in a split beryllium Hopkinson bar with strain gages as the reference measurement. The ENDEVCO 7270A* in a TO5 mechanical package has acceptable performance in-axis and cross-axis for these environments. However, packaging for a specific application may change the TO5 performance.

*Reference to a commercial product implies no endorsement by SNL or the Department of Energy or lack of suitable substitute.

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In-Axis and Cross-Axis Characterization of the ENDEVCO 7270A* Accelerometer in a TO5 Mechanical Package

Introduction

Sandia National Laboratories (SNL) conduct impact experiments for a variety of structures. These impact experiments include earth and rock penetrator experiments in which a penetrator structure is propelled at velocities of 1000 fps into earth or rock. During an impact experiment, metal to metal contact may occur within the structure and produce high frequency, high amplitude shocks. The ENDEVCO 7270A-60K* piezoresistive accelerometer die has been repackaged into a TO5 mechanical package in an attempt to lower cost and increase high-g survivability for high-volume production including impact fuzes and other components that must survive these environments.

In this report, the ENDEVCO 7270A* in a TO5 mechanical package will be referred to as the ENDEVCO 7270A-M2*. The TO5 package and the orientation of the ENDEVCO 7270A* inside the package are shown in Figure 1. A limited number of the ENDEVCO 7270A-M2 with only one range, 60,000 g, were available for this characterization. Every reference to the accelerometer characterization therefore refers to the ENDEVCO 7270A-M2 with a 60,000 g range. A titanium Hopkinson bar with an ENDEVCO 7270A-M2 on a flyaway fixture was used for in-axis characterization up to 25,000 g. for a bandwidth of DC - 10,000 Hz. The reference measurement for the in-axis characterization is a commercial, laser doppler vibrometer* (LDV), the Polytec PI Model OFV-3000 controller and Model OFV-302 sensor head*.

A bandwidth of at least 10 kHz is needed for many applications because more sophisticated analyses are being performed with the experimental data. Additionally, requirements are being made to qualify components for frequency ranges of 10 kHz. For example, Army research has found that armored vehicle components can be damaged by the high frequency content of ballistic shock [1, 2, 3]. To enhance survivability of the new generation of combat vehicles, the Army has specified a minimum frequency range of 10 kHz for the design and qualification of components. Qualification to even higher frequencies is desired, if reasonably possible, for other applications such as pyroshock environments on satellites.

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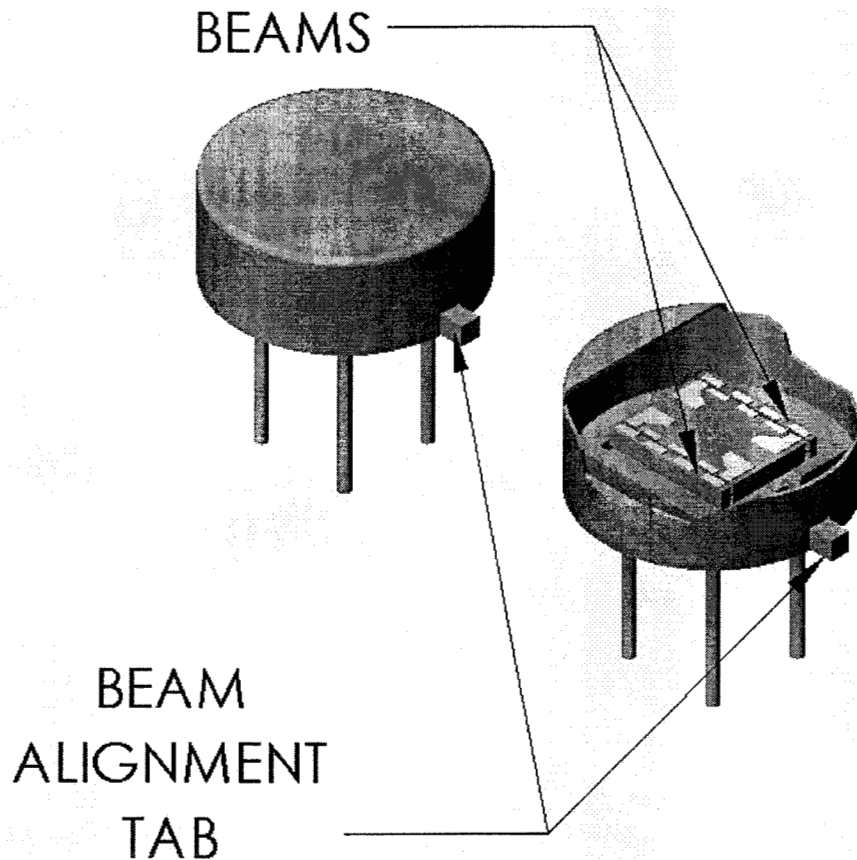


Figure 1: ENDEVCO 7270A-60K in the TO5 Mechanical Package (ENDEVCO 7270A-M2).

Results of cross-axis characterizations of the ENDEVCO 7270A-M2 subjected to compressive shocks in a split beryllium Hopkinson bar configuration are also presented. Beryllium is used for the cross-axis compressive mechanical shocks because of its low Poisson's ratio, 0.07. The result is that beryllium has negligible response in the accelerometer's sensitive axis, so these cross-axis experiments may be considered pure cross-axis environments. The reference measurements for cross-axis characterizations are strain gages.

Hopkinson Bar Configurations

The titanium Hopkinson bar configuration for characterizing accelerometers for normal or in-axis input is shown in Figure 2. Normal input in this configuration is an input that is normal to the mounting surface. Two different orientations were used for the in-axis characterization: the compressive shock applied through the base or pin side and the compressive shock applied through the top. A flyaway configuration was used because the TO5 package is bonded to the shock apparatus with a thin layer of high strength epoxy. The removal of the epoxy and the

ENDEVCO 7270A-M2 post-test destroys the mounting surface and the ENDEVCO 7270A-M2. Consequently, it is easier to use a flyaway configuration than to damage and then resurface the end of a conventional Hopkinson bar where the ENDEVCO 7270A-M2 would be bonded. The two configurations for the in-axis characterization of the ENDEVCO 7270A-M2 are shown in Figures 3 and 4.

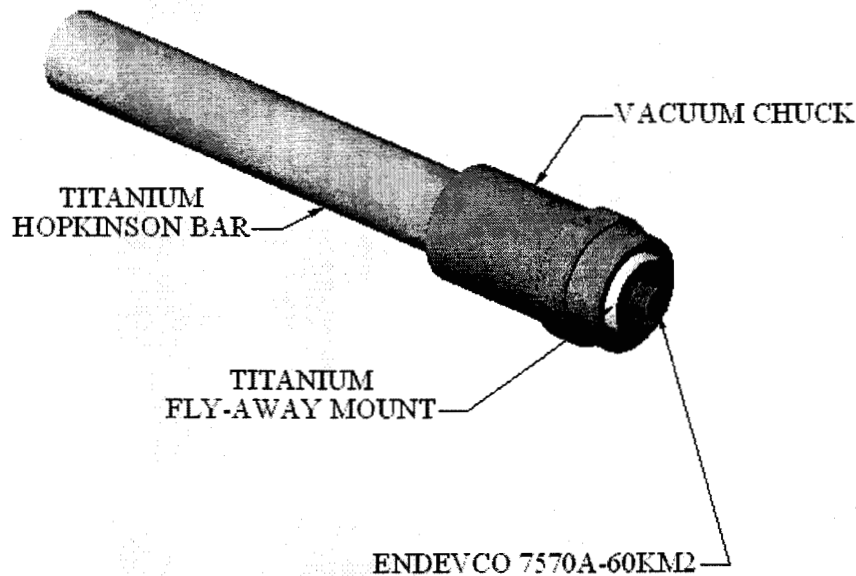
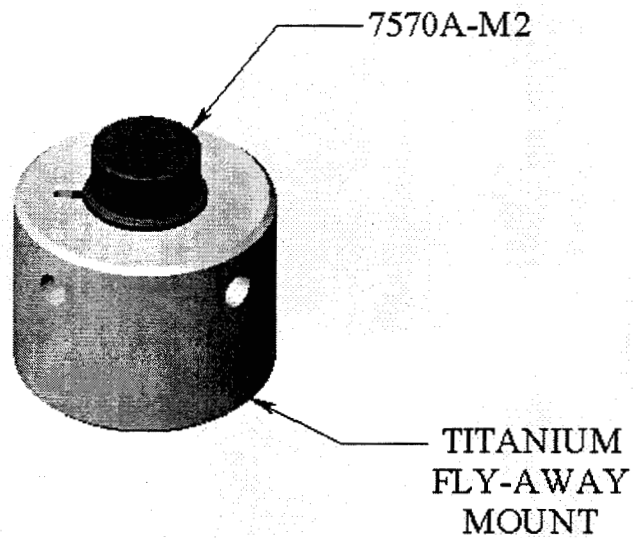
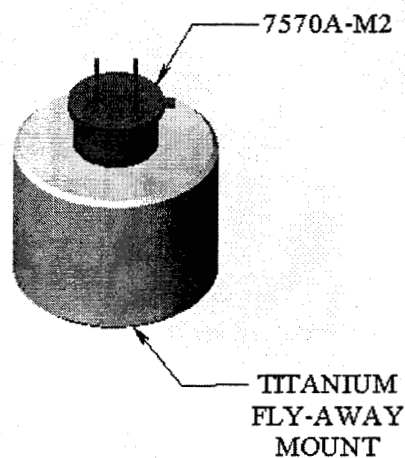


Figure 2: Titanium Hopkinson Bar Configuration for In-Axis Characterizations (0.75 in. Diameter).

Cross-axis sensitivity of the piezoresistive accelerometers has been studied with the beryllium split Hopkinson bar configuration shown in Figures 5, 6, and 7. An in-axis response is the response of an accelerometer whose sensitive axis is in the direction of the shock. An out-of-axis or cross-axis response is the response of an accelerometer whose sensitive axis is not in the direction of the shock but is perpendicular to the to the direction of the shock. With beryllium's Poisson's ratio of 0.07, the cross-axis performance is obtained with negligible motion in the accelerometer's sensitive axis. Strain gages co-located with the ENDEVCO 7270A-M2 are used as the reference measurement. The strain gages have been certified as the reference measurement for a bandwidth of dc to 10 kHz with an



**Figure 3: Hopkinson Bar Flyaway for In-Axis ENDEVCO 7570A-M2
Evaluation Through the Base.**



**Figure 4: Hopkinson Bar Flyaway for In-Axis ENDEVCO 7570A-M2
Evaluation Through the Top.**

uncertainty of + 6% [4]. The beryllium Hopkinson bar capability is unique to the SNL Mechanical Shock Laboratory and has been described in detail in a previous publication [5].

No special preparations of the beryllium Hopkinson bar interfaces with the inserts are made other than insuring that the surfaces are flat and polished. Careful alignment of the bars and the insert is required. All Hopkinson bars used for the results shown in this report are freely supported. Both time domain calculations, as a percent difference from the reference measurement (LDV or strain gages), and frequency domain calculations, as frequency response functions, are made with the Hopkinson bar data.

The Mechanical Shock Laboratory Hopkinson bars, used for accelerometer characterizations, are made of either 6 AL, 4V titanium alloy (6% aluminum and 4% vanadium) or beryllium (99% pure) with a 0.75 inch diameter. The titanium bar is 72 in. long, and the beryllium bars are 50 in. long. Each bar is supported in a way that allows it to move freely in the axial direction. A low pressure air gun is used to fire a 3 inch long titanium (for titanium) or magnesium (for beryllium) projectile at the end of the bar. This impact creates a stress pulse that propagates toward the opposite end of the Hopkinson bar. Regulating the air gun pressure that determines the impact speed controls the amplitude of the pulse. Placing a number of index cards on the impact surface controls the shape (approximately a half sine) and duration of the pulse.

For in-axis characterizations, the LDV is located at the end of the titanium bar on which the accelerometer is mounted and measures velocity at a point next to the accelerometer. This LDV with high frequency (up to 1.5 MHz) and high velocity (10 m/s) capability was purchased from a commercial source and has been certified by the Primary Electrical Standards Department at SNL. For the 1000 mm/s/V range (positive velocity), the total uncertainty with approximately a 95% confidence level for the velocity is +5%. When the LDV is used over 90% of its range, this LDV has a +2-3% uncertainty for all specified frequencies and velocities. The uncertainty decreases for decreasing velocity scales. The LDV provides a reference velocity measurement for velocities up to 10 m/s and for frequencies up to 1.5 MHz. This reference measurement provides information in a bandwidth that is not available from strain gages that are generally considered to have a bandwidth of no greater than dc-40 kHz. Since these piezoresistive accelerometers and the Hopkinson bars have resonances at these high frequencies of 100's of kHz, the LDV is a useful diagnostic tool. Ref. [6] gives the details of the certification process.

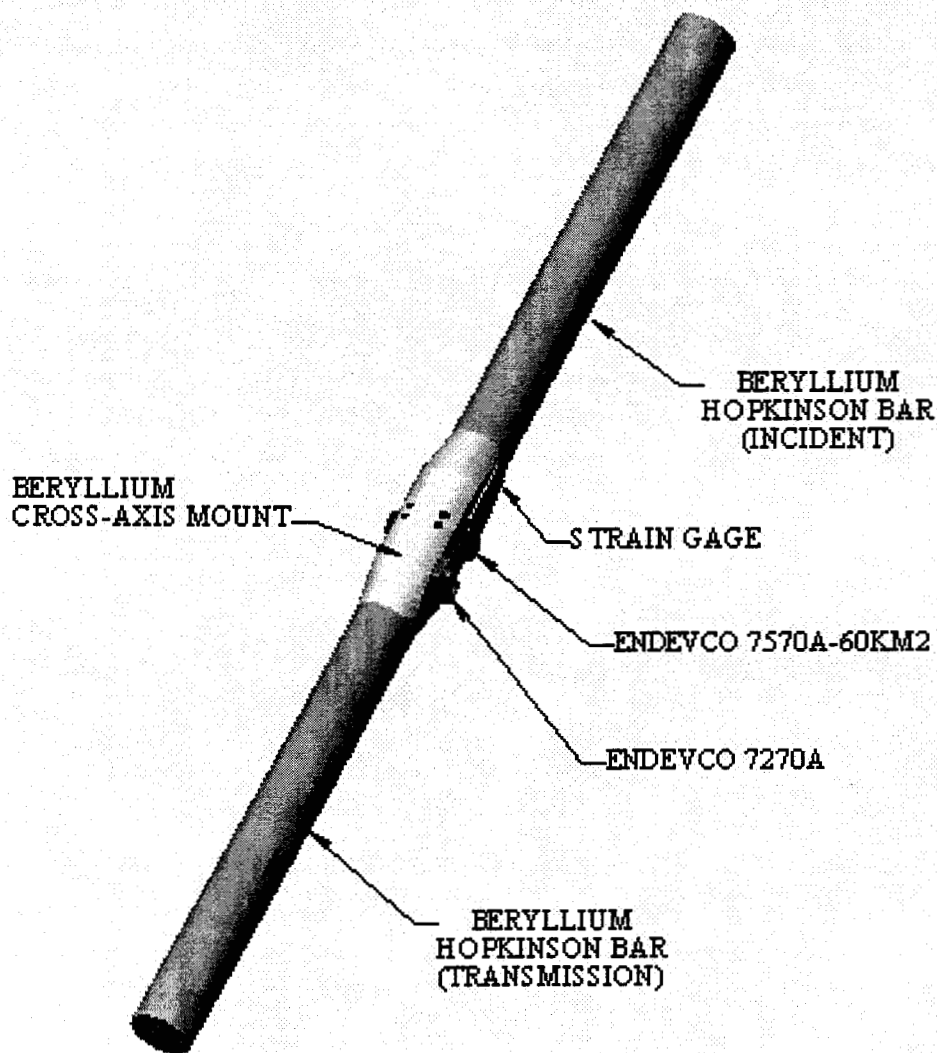


Figure 5: Split Beryllium Hopkinson Bar Configuration for Cross-Axis Input (0.75 in. Diameter).

Hopkinson Bar Analysis for In-Axis Response

The theory of stress wave propagation in a Hopkinson bar is well documented in the literature [7, 8]. The results of this theory are summarized as follows:

A Hopkinson bar is defined as a perfectly elastic, homogeneous bar of constant cross-section.

A stress wave will propagate in a Hopkinson bar as a one-dimensional elastic wave without attenuation or distortion if the wavelength, λ , is large relative to the diameter, D , or $10D \leq \lambda$.

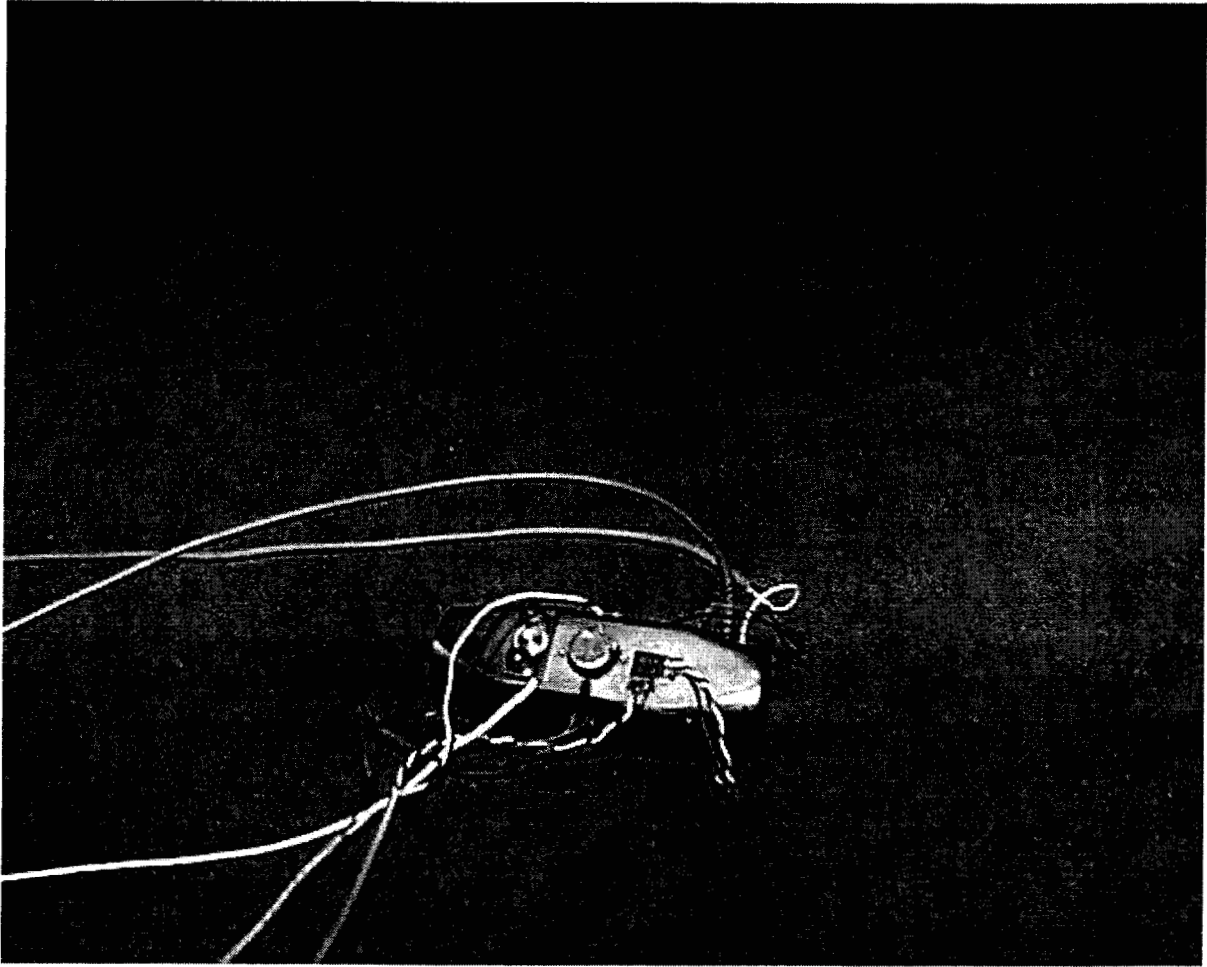


Figure 6: One Side of the Insert for Split Beryllium Hopkinson Bar Configuration with 0.75 in. diameter.

For a one-dimensional stress wave propagating in a Hopkinson bar, the motion of a free end of the bar as a result of this wave is:

$$v = 2c\epsilon \quad (1)$$

or,

$$a = 2c \frac{d\epsilon}{dt} \quad (2)$$

where,

$$c = \sqrt{\frac{E}{\rho}} \quad (3)$$

and v and a are the velocity and acceleration, respectively, of the end of the bar, c is the wave

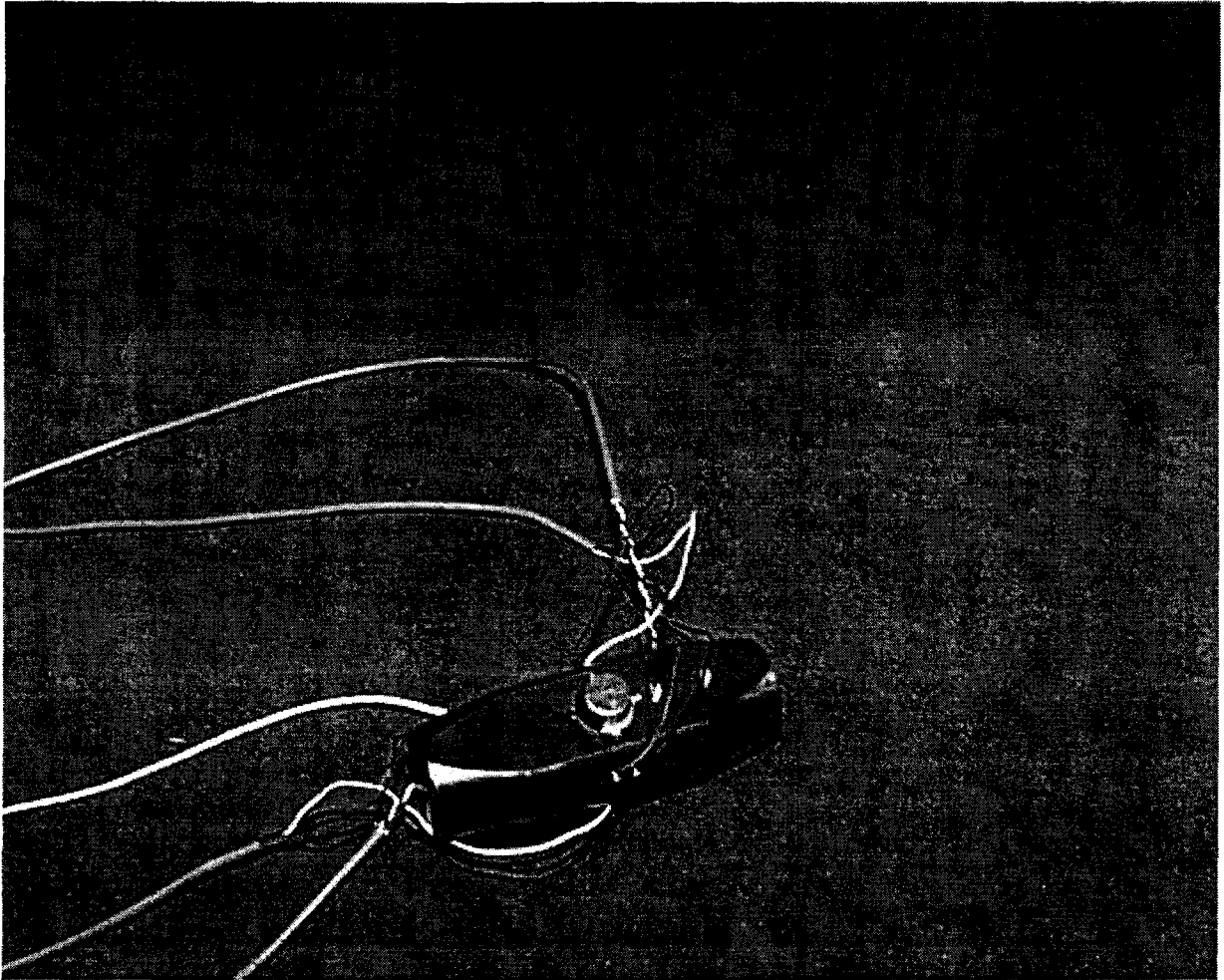


Figure 7: Second Side of the Insert for Split Beryllium Hopkinson Bar Configuration with 0.75 in. diameter.

propagation speed in the bar, E is the modulus of elasticity, ρ is the density for the Hopkinson bar material, and ε is the strain measured in the bar at a location that is not affected by reflections during the measurement interval.

The motion of an accelerometer mounted on the end of the bar will be governed by equations (1) and (2) if the mechanical impedance of the accelerometer is much less than that of the bar or if the thickness of the accelerometer is much less than the wavelength. The requirement on the strain gage is that the gage length (g.l.) be much less than the wavelength or $\lambda \geq 10 \text{ g.l.}$

In-Axis Accelerometer Performance

To assess in-axis performance, the velocity (strain gages or LDV) and acceleration (accelerometer) records can be compared by converting to either velocity or acceleration as shown in (1) and (2). Since it was desired to preserve the frequency response of the data, acceleration is used for the comparison of the data. Consequently, the time derivative of the strain records was required, and the resulting signal may be contaminated by high frequency noise created in the process of calculating the derivative. This problem was essentially eliminated by: 1) adequate sample rate of 500 kHz or higher; 2) low pass digital filtering with a cutoff frequency well above the frequency range of interest (10 kHz); and most importantly, 3) an accurate differentiation algorithm which was derived using the Fourier series reconstruction techniques in [9]. This algorithm results in an exact derivative of the digitized signal providing the Sampling Theorem has not been violated, that is, the data is not aliased [10]. With the reference acceleration and the accelerometer response, in-axis performance may be assessed in both the time-domain and the frequency domain.

The ENDEVCO 7270A-M2 accelerometer on the flyaway was attached directly to the end of a titanium Hopkinson bar with a vacuum chuck and subjected to shock pulses of about 10,000 g and 25,000 g with nominal pulse duration of about 45-50 μ s in all cases. The magnitude of the ENDEVCO 7270A-M2 responses was compared to the acceleration magnitude derived from the LDV measurements. Percent deviations in peak amplitude varied from 2% to 6%. Time history plots comparing the accelerometer response with the reference measurement of the LDV made on the flyaway next to the ENDEVCO 7270A-M2 accelerometer are shown in Figures 8-11. Time history plots comparing the accelerometer response with the reference measurement of the LDV made on the ENDEVCO 7270A-M2 top (input through the base) are shown in Figures 12 and 13. The corresponding Fourier transform of the LDV derived acceleration in Figure 13 is in Figure 14 where a resonance at 30 kHz for the TO5 top is evident. Time history plots comparing the accelerometer response with the reference measurement of the LDV made on the ENDEVCO 7270A-M2 base (input through the top) are shown in Figures 15 and 16. The 30 kHz resonance for the TO5 top is not evident in either the time history data or the corresponding Fourier transform (not shown) of the LDV derived acceleration for the base.

Next, frequency response functions (frf's) were calculated for the shock levels of 10,000 g and 25,000 g with nominal pulse duration of about 45-50 μ s so that a quantitative evaluation could be made of the frequency response for the ENDEVCO 7270A-M2. The process of calculating these requires five consistent shocks at each level. The reference acceleration data, calculated from the LDV,

and the accelerometer response data were used to calculate a frf, $H(j\omega)$, using the equations below [11].

$$H(j\omega) = \frac{H_1 + H_2}{2} \quad (4)$$

where,

$$H_1(j\omega) = \frac{\sum_{n=1}^5 G_{xy}}{\sum_{n=1}^5 G_{xx}} \quad (5)$$

and

$$H_2(j\omega) = \frac{\sum_{n=1}^5 G_{yy}}{\sum_{n=1}^5 G_{yx}} \quad (6)$$

and where G_{xy} is the cross-spectrum between the reference acceleration, x , and the accelerometer response, y ; G_{yx} is the cross-spectrum between the accelerometer response, y , and the reference acceleration, x ; G_{yy} is the auto-spectrum of the accelerometer response, y ; and G_{xx} is the auto-spectrum of the

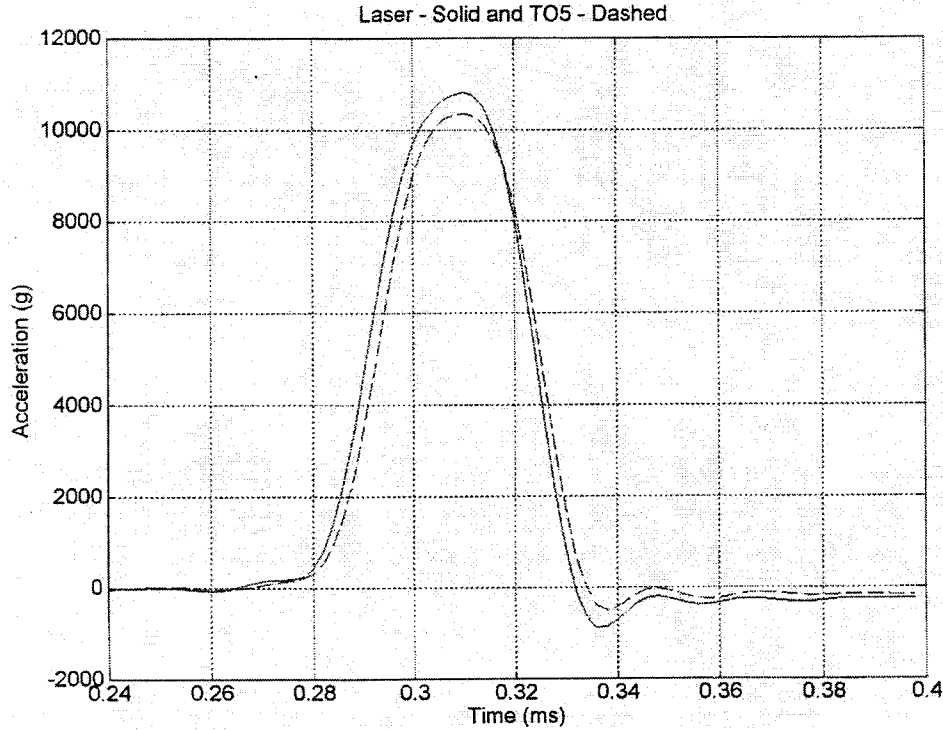


Figure 8: In-Axis ENDEVCO 7570A-M2 Evaluation Through Base at 10,000 g.

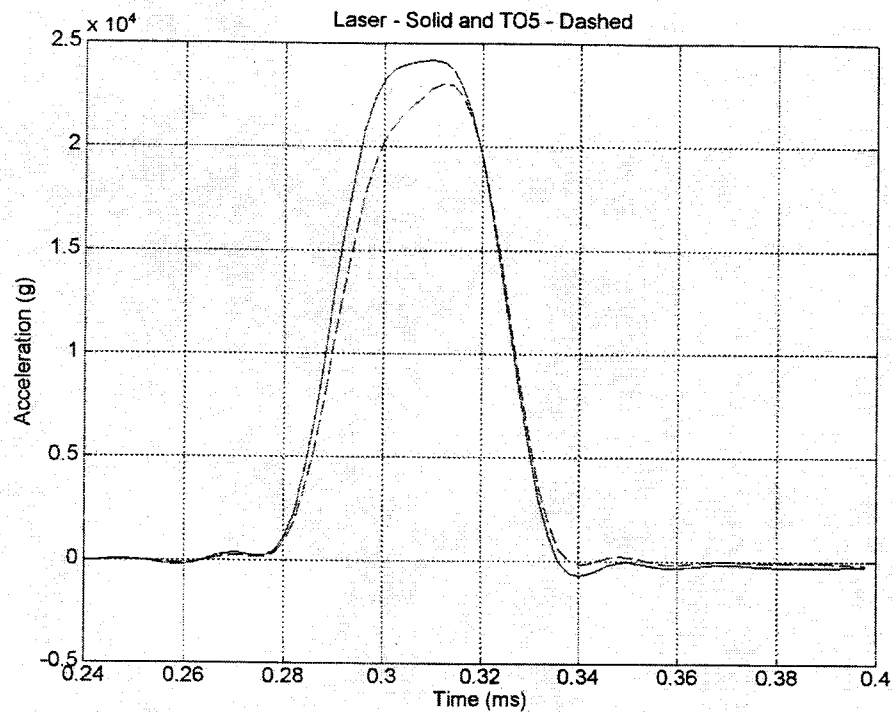


Figure 9: In-Axis ENDEVCO 7570A-M2 Evaluation Through Base at 25,000 g.

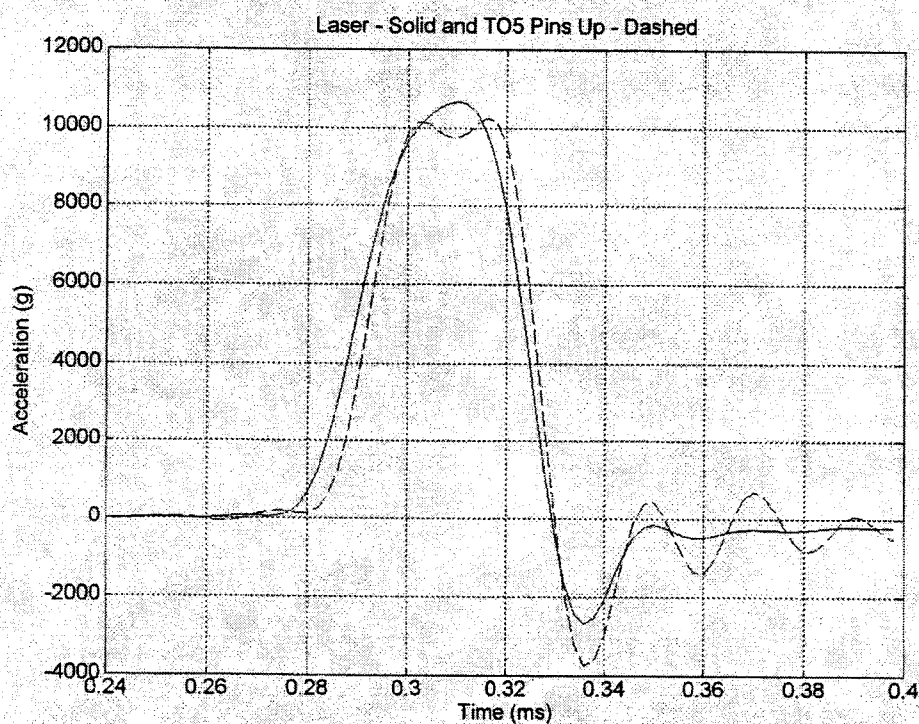


Figure 10: In-Axis ENDEVCO 7570A-M2 Evaluation Through Top at 10,000 g.

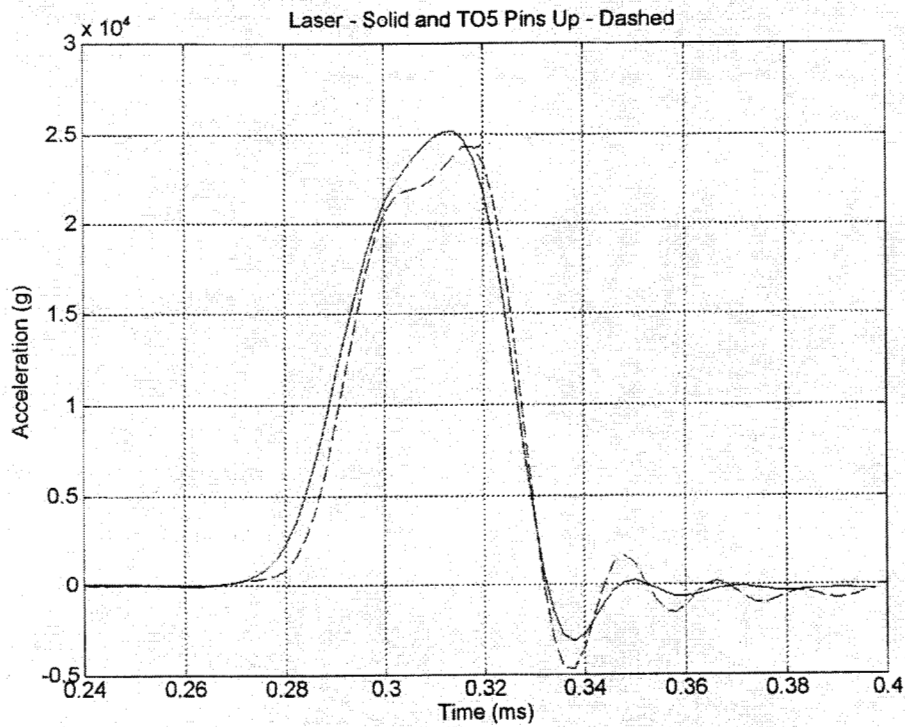


Figure 11: In-Axis ENDEVCO 7570A-M2 Evaluation Through Top at 25,000 g.

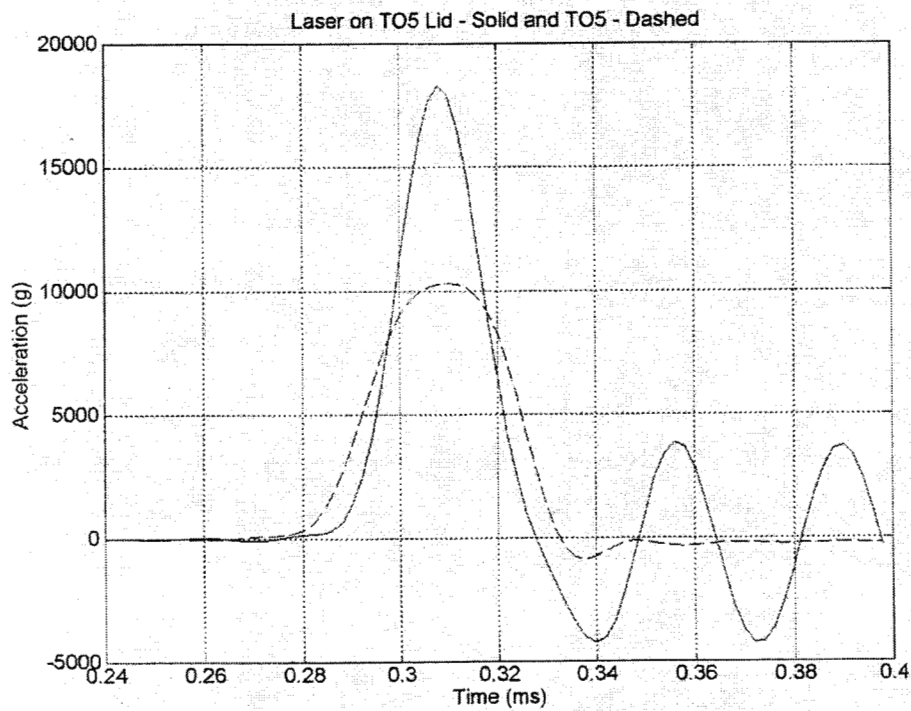


Figure 12: In-Axis ENDEVCO 7570A-M2 Evaluation Through Base at 10,000 g with LDV on TO5 Top.

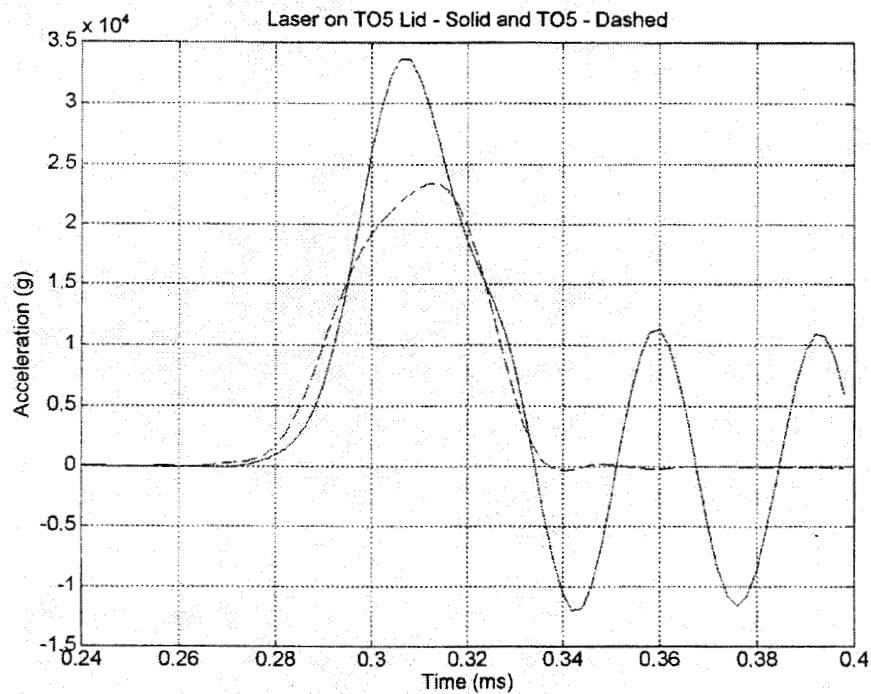


Figure 13: In-Axis ENDEVCO 7570A-M2 Evaluation Through Base at 25,000 g with LDV on TO5 Top.

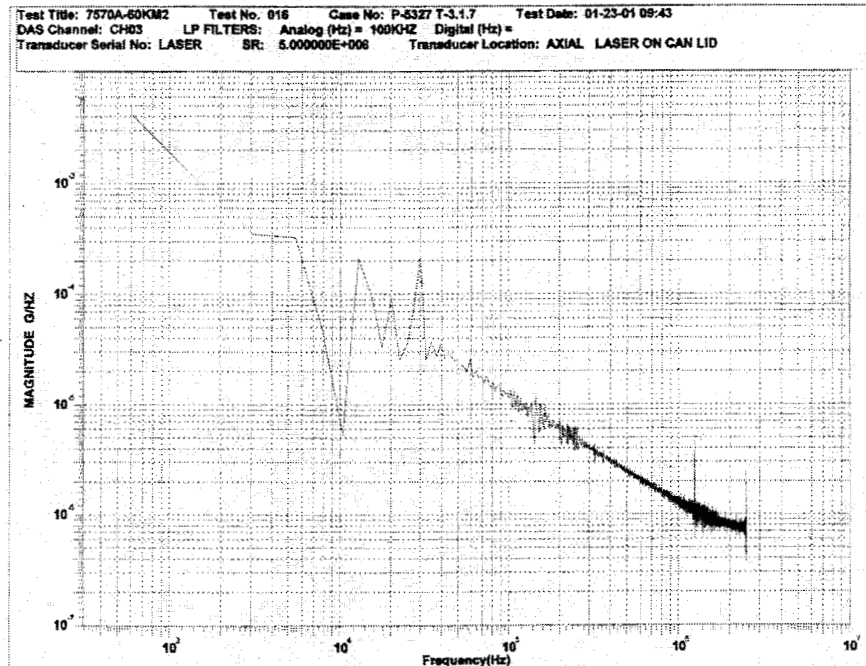


Figure 14: Fourier Transform for LDV Derived Acceleration in Figure 13.

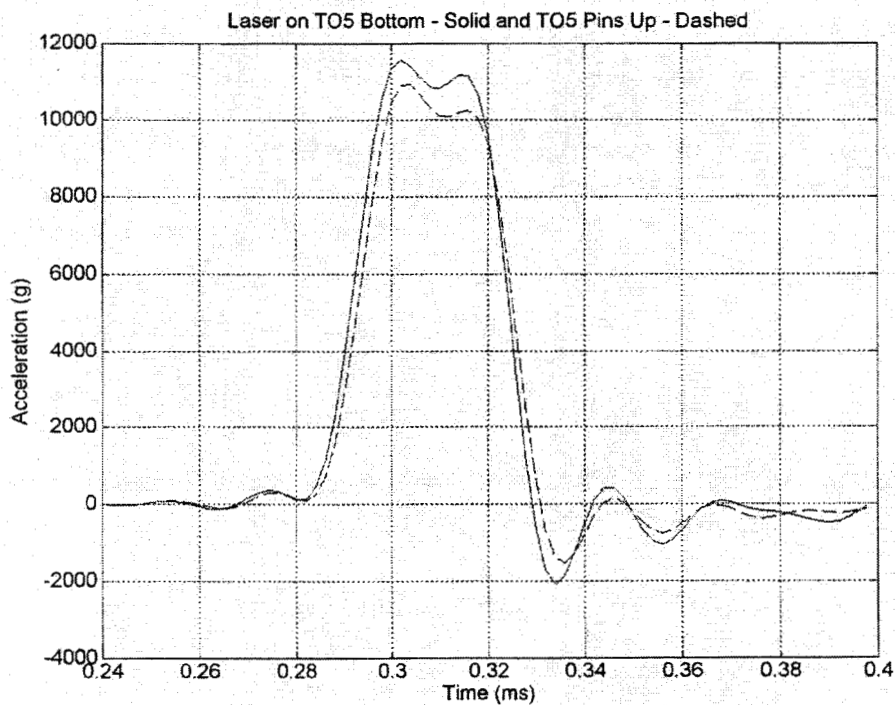


Figure 15: In-Axis ENDEVCO 7570A-M2 Evaluation Through Top at 10,000 g with LDV on TO5 Base.

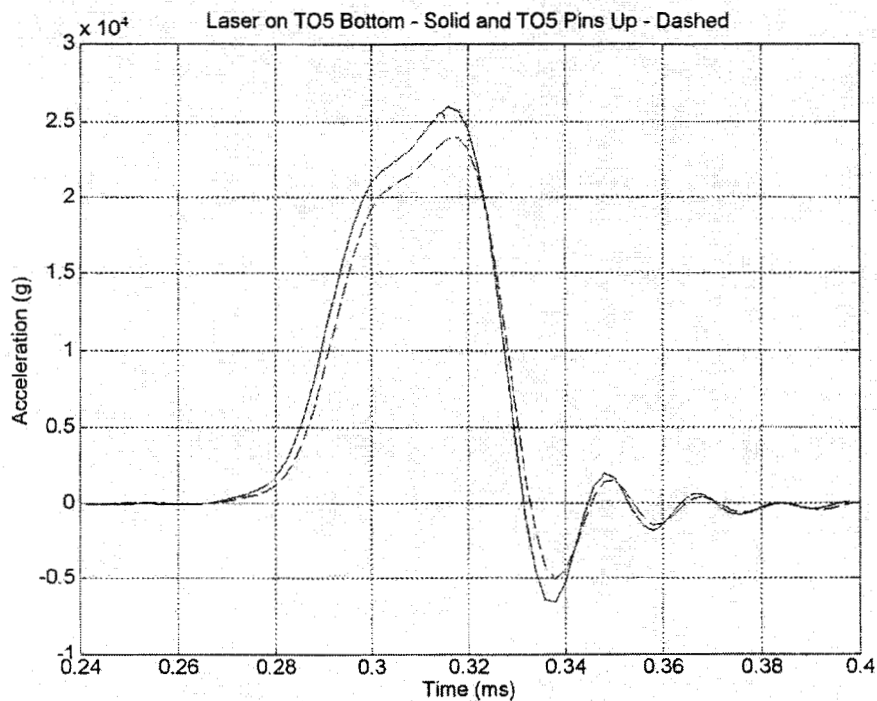


Figure 16: In-Axis ENDEVCO 7570A-M2 Evaluation Through Top at 25,000 g with LDV on TO5 Base.

reference acceleration, x . The frf, H_1 is biased by the error on the reference acceleration, and the frf, H_2 is biased by the error on the accelerometer response. The Hopkinson bar data for these frf calculations have noise on both the reference acceleration and the accelerometer response, so the average of the two frf's in (4) is used. The summations are performed for the ensemble of five reference accelerations and their corresponding accelerometer responses. The coherence, $\gamma_{xy}^2(j\omega)$, was also calculated for an ensemble of five data sets according to the equation [11]

$$\gamma_{xy}^2(j\omega) = \frac{H_1}{H_2} \quad (7)$$

as a measure of the linearity between the reference acceleration and the accelerometer response and of the noise in these data.

The frf magnitude and phase are shown in Figures 17 and 18, respectively. The frf's show excellent performance for the ENDEVCO 7270A-M2 accelerometer. Any structural response for the Hopkinson bar flyaway has been eliminated by using the LDV measurement next to the ENDEVCO 7270A-M2 accelerometer as the reference measurement in the frf calculations. FRF Coherence was calculated and was greater than 0.99 for the bandwidth up to 10,000 Hz that is shown in Figures 17-18. Above 10,000 Hz, the coherence is not acceptable. This occurs primarily because of the pulse duration for these data and has been discussed previously in detail [4, 5].

Hopkinson Bar Analysis for Cross-Axis Response

The axial motion, a , at a location in the Hopkinson bar other than the free end is

$$a = c \frac{d\varepsilon}{dt} \quad (8)$$

where ε is the axial strain. The radial motion, y , is

$$y = r\varepsilon_r \quad (9)$$

where r is the radius of the Hopkinson bar and ε_r is the radial strain. Since the relationship between axial and radial strain is

$$\varepsilon_r = \mu\varepsilon \quad (10)$$

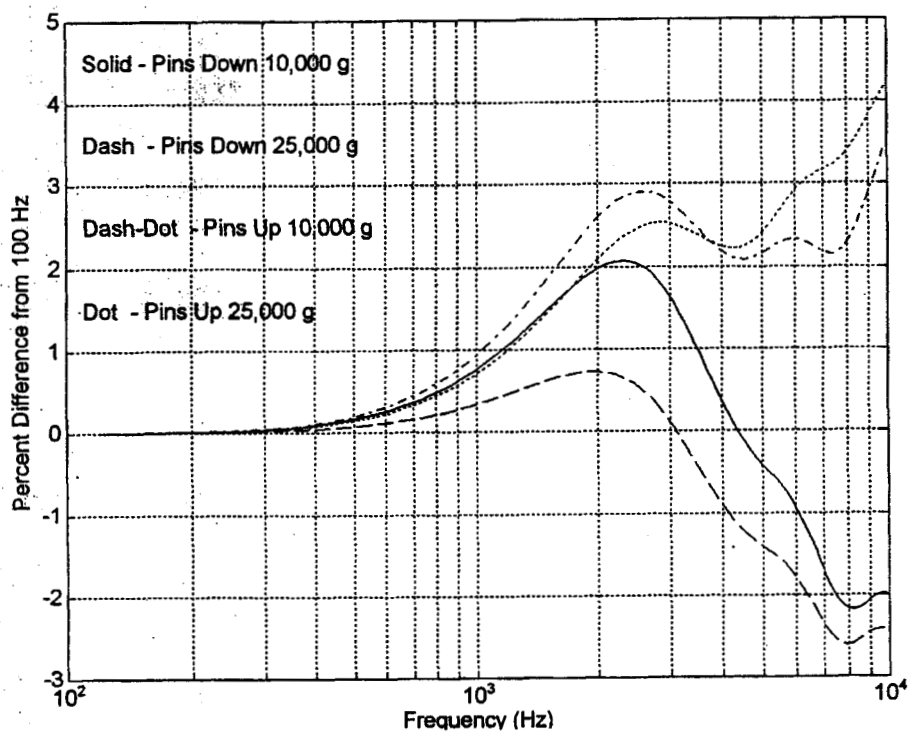


Figure 17: Frequency Response Function Magnitude for In-Axis ENDEVCO 7570A-M2 Evaluation.

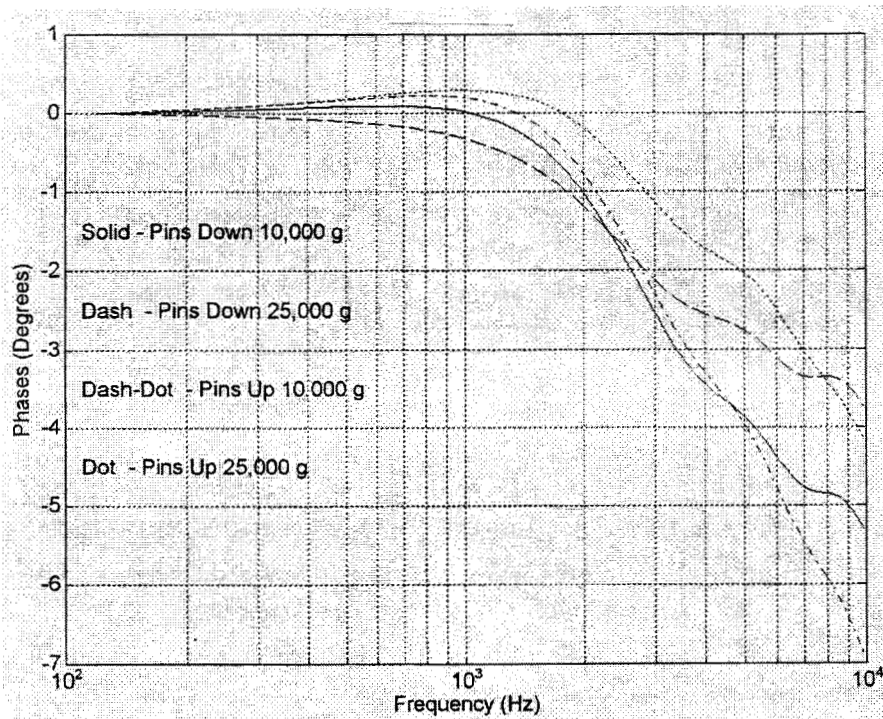


Figure 18: Frequency Response Function Phase for In-Axis ENDEVCO 7570A-M2 Evaluation.

where μ is Poisson's ratio, then the final expression for radial acceleration, a_y , is

$$a_y = \frac{\mu r}{c} \frac{da}{dt}. \quad (11)$$

A prediction of the axial and radial acceleration for the beryllium Hopkinson bar using the equations above is shown in Figure 19. Strain measurements co-located with the accelerometers on the insert in Figures 6-7 and in the split Hopkinson bar configuration in Figure 5 confirm previous measurements of Poisson's ratio as about 0.07 [5].

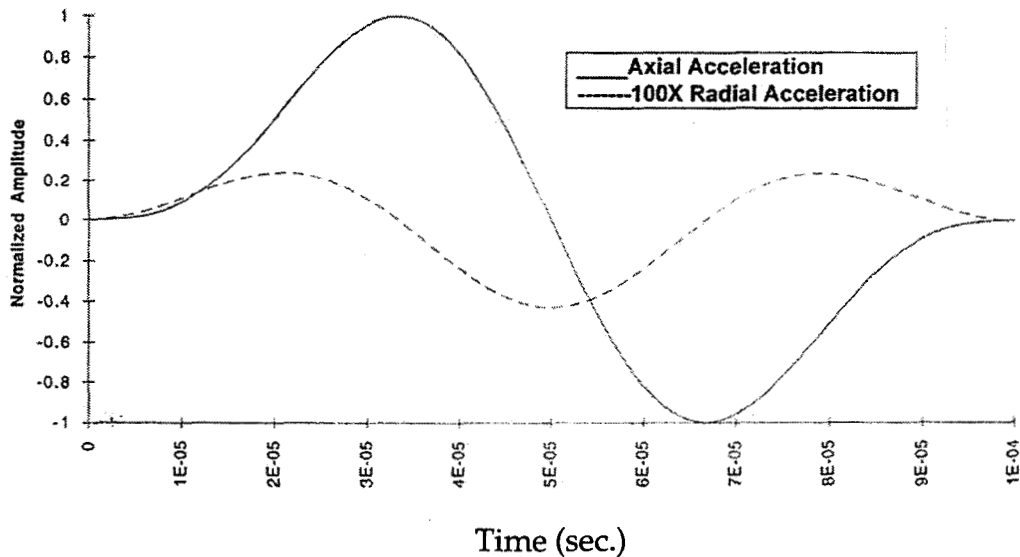


Figure 19: Theoretical Prediction of Axial and Lateral Accelerations for the Beryllium Hopkinson Bar.

Cross-Axis Accelerometer Performance

The axial strain response to the compressive wave on the beryllium insert is shown in Figure 20. The peak axial strain is about $200 \mu\epsilon$ and is the same peak amplitude used previously to characterize the cross-axis response of other ENDEVCO 7270A mechanical packages [5]. The precise orientation of the sensor in the ENDEVCO 7270A-M2 as shown in Figure 1 allows orientation of the sensor with the beams in line with the shock and oriented at 90° to the shock. Two ENDEVCO 7270A-M2 accelerometer responses measured on the insert responses for the two different orientations in Figures 6 and 7 are shown in Figures 21-22. The response in Figure 21 is base strain dominated because it does not correspond to either of the curves in Figure 19 but follows the general shape of the axial strain response in Figure 20. The orientation for this accelerometer on the insert is in Figure 6, and the beams are oriented at 90° to the compressive

wave. The response in Figure 22 is acceleration dominated because it has the same shape as the radial acceleration curve in Figure 19. The orientation for this accelerometer on the insert is in Figure 7, and the beams are parallel to the compressive wave.

Failure Mode Analysis

During one of the in-axis experiments for the ENDEVCO 7270A-M2 accelerometer, the accelerometer failed. The failure was indicated by a large change in resistance for one of four legs in the resistance bridge. The sensor probably saw a high frequency slap because the flyaway was cocked in the vacuum chuck. However, this type of environment occurs in the real world of shock measurements, and the failure was investigated by both the authors at SNL and Bob Sill at ENDEVCO. Figures 23-24 show high magnification pictures of the failed sensor. Figure 23 is a picture of the entire sensor shown schematically inside the TO5 package in Figure 1. There are eight piezoresistive elements between each beam and the center mass on the top and bottom of the sensor for a total of 32 piezoresistive elements. There is a single missing piezoresistive element in the bottom right hand corner. This single missing

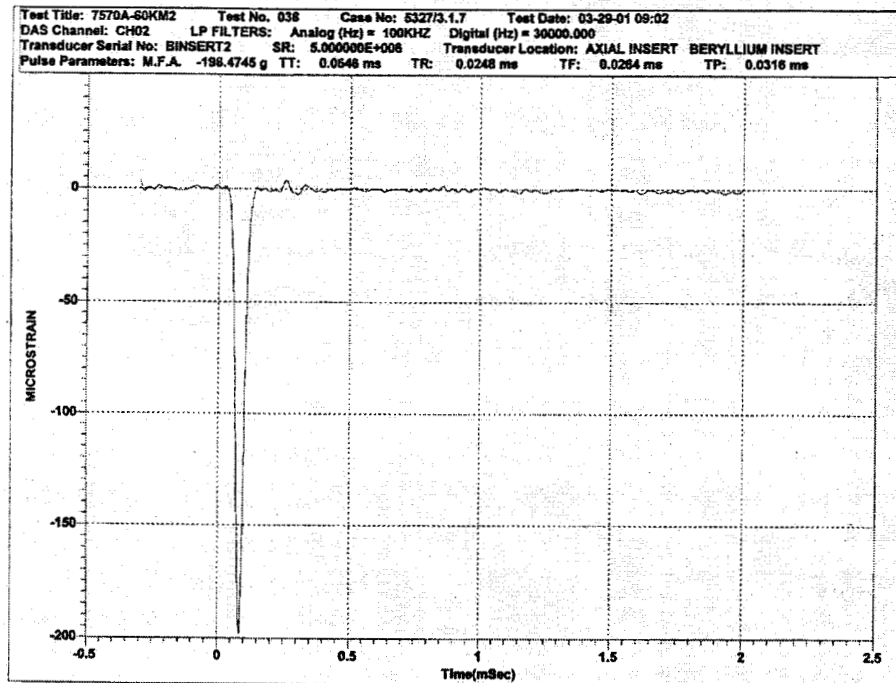


Figure 20: Axial Strain Response to Compressive Shock on the Beryllium Insert (0.75 in. Diameter).

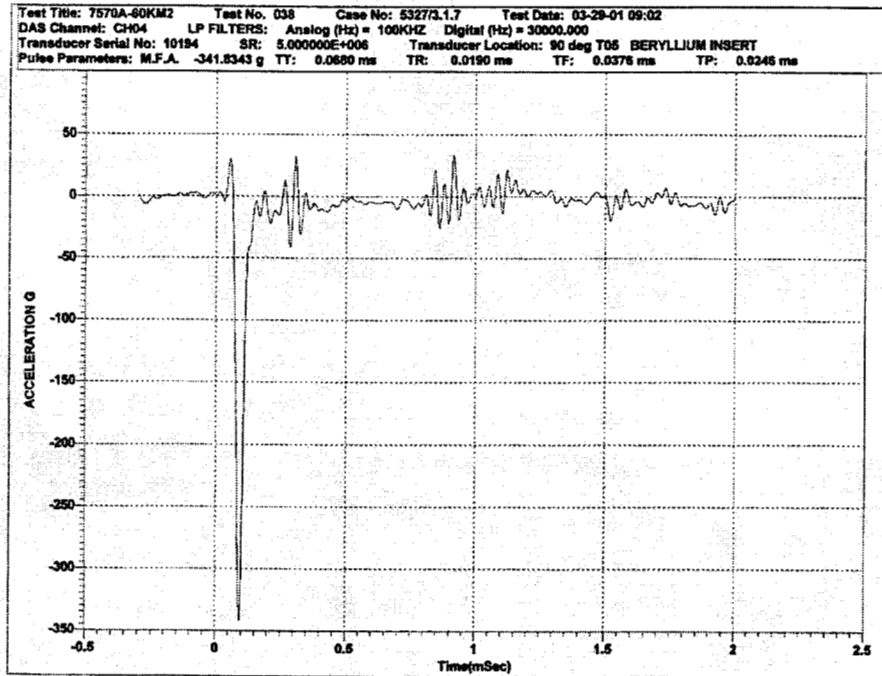


Figure 21: ENDEVCO 7270A-M2 Base Strain Response to Cross-Axis Input on the Beryllium Insert (Beams at 90° to Compressive Wave).

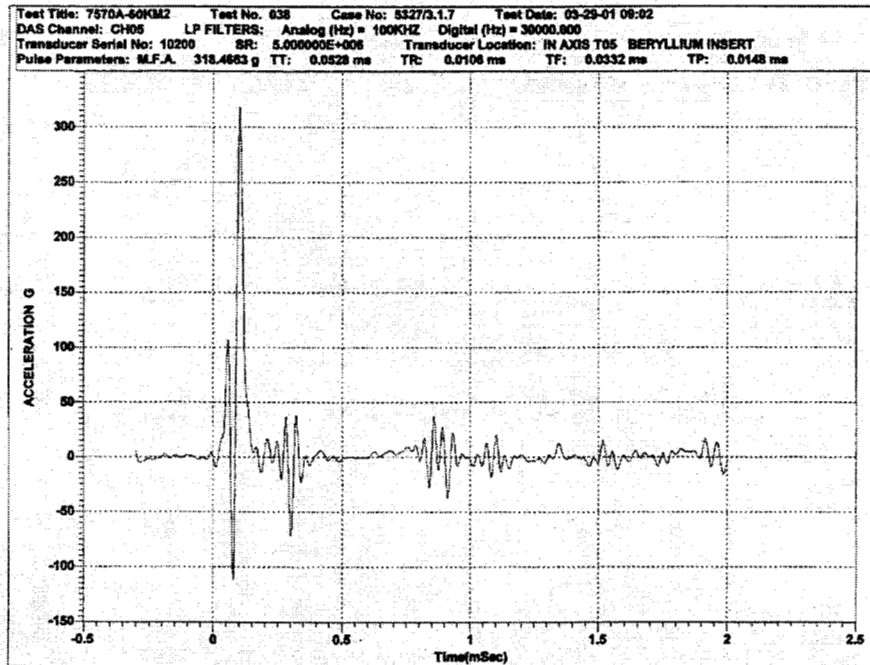
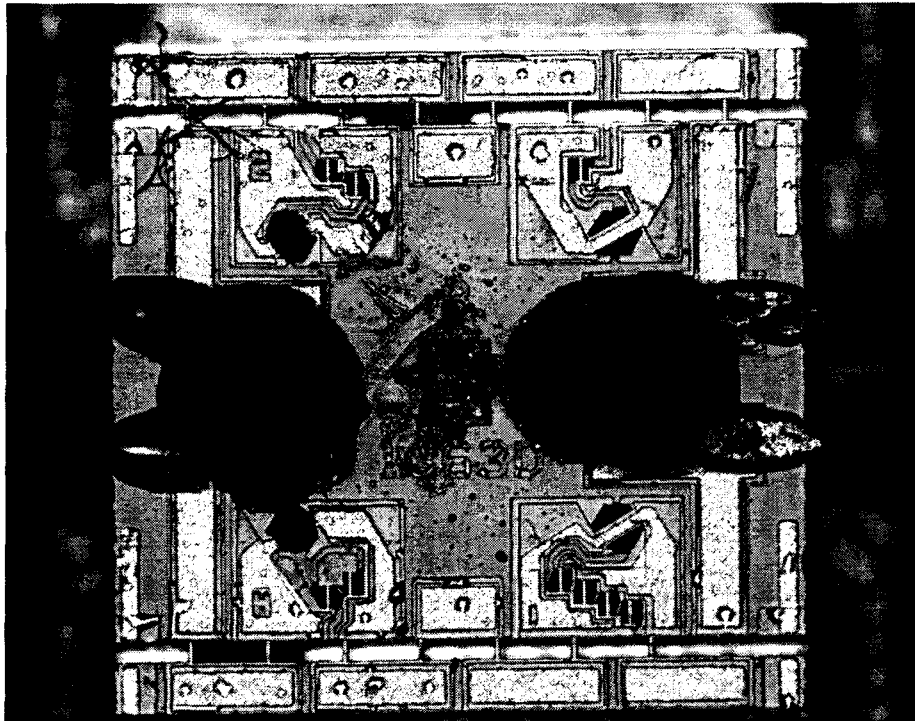


Figure 22: ENDEVCO 7270A-M2 Acceleration Response to Cross-Axis Input on the Beryllium Insert (Beams Parallel to Compressive Wave).

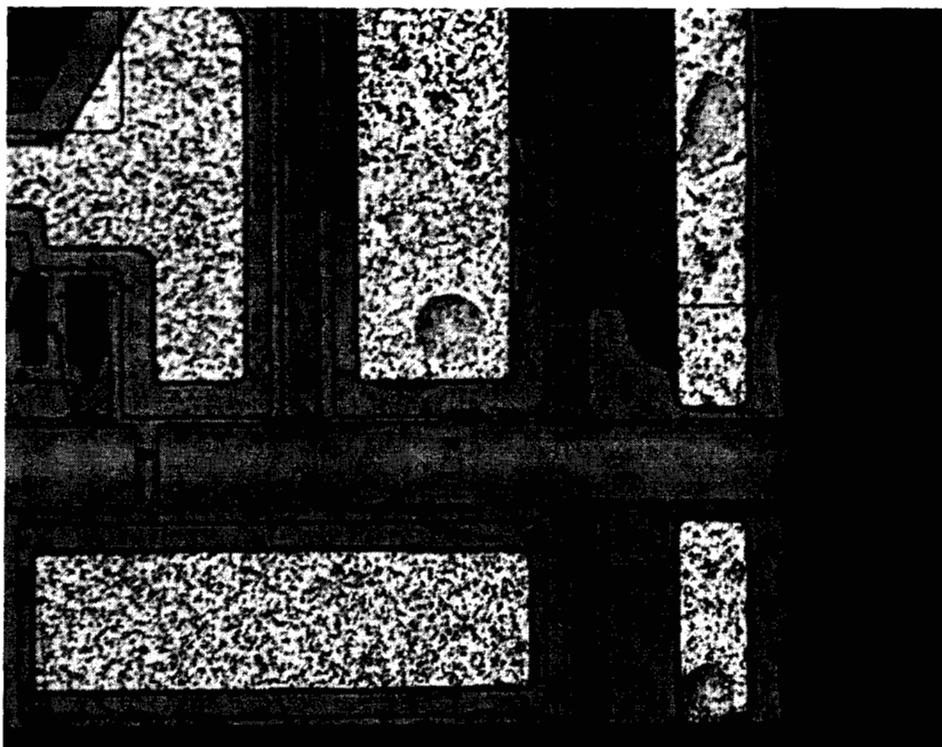
Dark masses on the two hinges connecting the two beams to the center mass indicate an un-etched mass of silicon caused by non-uniform etching in the manufacturing process. Since the hinge is stronger at these points, it is the probable reason that the piezoresistive element broke. Also, at the opposite end of the thicker, stronger hinge, the highest strain occurred and consequently the element failed. Particle impact from the debris left on the die from the manufacturing process is also a possibility because considerable debris is evident.



**Figure 23: Failed ENDEVCO 7270A-M2 Accelerometer
With Missing Piezoresistive Element
in Lower Right Hand Corner.**

Uncertainty Analysis

The uncertainty in these measurements and results are attributed to: uncertainty in the accelerometer sensitivity, the reference measurement (strain gages or LDV), the data acquisition system, and accelerometer response due to attachment variation (epoxy thickness, epoxy uniformity etc.). The sensor and data acquisition uncertainty is monitored on a continual basis in the SNL Mechanical Shock Laboratory as required by the SNL Specification 9958003 [12]. These requirements include the performance of both the hardware (sensors, amplifiers, digitizers etc.) and the IMPAX software that controls the data acquisition system



**Figure 24: Enlarged View of Missing Piezoresistive Element
in Lower Right Hand Corner.**

through a computer [13, 14, 15]. The 9958003 specification allows an accuracy of $\pm 10\%$ for amplitude, $\pm 5\%$ for duration, and $\pm 8\%$ for rise and fall time for any measured pulse greater than $50 \mu\text{s}$ in duration. The current data acquisition system and software meet these requirements within $\pm 0.5\%$, and documentation of these results is maintained in the Mechanical Shock Laboratory. Consequently, the uncertainty in these measurements is the uncertainty in the accelerometer calibration, $\pm 5\%$ [5], the uncertainty of the reference measurement 6% [4, 6], and the uncertainty in accelerometer attachment variation. These three uncertainties are considered random, so they may be combined in an uncertainty analysis with a 95% confidence level as [16-17].

$$w_T = \sqrt{w_s^2 + w_{rf}^2 + w_a^2} \quad (12)$$

where: w_T = total uncertainty,
 w_s = accelerometer sensitivity uncertainty, 5% ,
 w_{rf} = uncertainty of the reference measurement, 6% , and
 w_a = accelerometer attachment variation, $\pm 5\%$.

The value of the total uncertainty, w_T , is $\pm 9\%$ and is typical for the measurements made in the SNL Mechanical Shock Laboratory.

Conclusions

Results to 10 kHz show the ENDEVCO 7270A-M2 has similar response for in-axis shocks when the compressive shock wave is applied through either the TO5 base or the TO5 top. A resonance is noted for in-axis shock applied through the base at about 30 kHz that is not apparent in the other orientation. The results of the in-axis studies for this TO5 mechanical package are similar to the results obtained for other mechanical packages and confirm the manufacturer's performance specifications for the accelerometers. The cross axis response of the ENDEVCO 7270A-M2 may be either base strain or acceleration. The accelerometer meets the manufacturer's specifications for base strain and cross axis sensitivity. The ENDEVCO 7270A in a TO5 mechanical package has acceptable performance in-axis and cross-axis for these environments. However, packaging for a specific application may change the TO5 performance. For example, encapsulation of the TO5 should extend its frequency response and eliminate the resonance at 30 kHz. But, encapsulation may introduce other issues or problems because the mechanical integrity of the TO5 package would then become a function of both the strength and the rigidity of the encapsulation as well as the mechanical package.

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